



NO  
A Fee

94CR091

00/313476

1 1. REFERENCES

2 <sup>201</sup> Which

3 This is a continuation-in-part application of U.S. Patent Application, serial number  
4 223,251, filed April 4, 1994, <sup>now U.S. Patent No. 5,504,603,</sup> entitled "Optical Compensator for Improved Gray Scale  
5 Performance in Liquid Crystal Display."

Wjm  
10-15-96

7 2. BACKGROUND OF THE INVENTION

9 This invention is concerned with the design of liquid crystal displays (LCDs)  
10 and, more particularly, with techniques for maximizing the field of view of such  
11 displays by maintaining a high contrast ratio and minimal variance in relative gray  
12 levels over a wide range of viewing angles. These goals are achieved through the  
13 fabrication and manufacture of LCDs using O-plate technology.

15 2.1 LCD Technology Overview

17 Liquid crystals are useful for electronic displays because polarized light  
18 traveling through a liquid crystal layer is affected by the layer's birefringence, which  
19 can be changed by the application of a voltage across the layer. By using this effect,  
20 the transmission or reflection of light from an external source, including ambient  
21 light, can be controlled with much less power than is required for the luminescent  
22 materials used in other types of displays. As a result, liquid crystal displays are now  
23 commonly used in a wide variety of applications, such as, for example, digital  
24 watches, calculators, portable computers, and many other types of electronic equip-  
25 ment. These applications highlight some of the advantages of LCD technology in-  
26 cluding very long operational life in combination with very low weight and low power  
27 consumption.

2

1           The information content in many liquid crystal displays is presented in the  
2 form of multiple rows of numerals or characters, which are generated by segmented  
3 electrodes deposited in a pattern on the display. The electrode segments are  
4 connected by individual leads to electronic driving circuitry. By applying a voltage to  
5 the appropriate combination of segments, the electronic driving circuitry controls the  
6 light transmitted through the segments.

7  
8           Graphic and television displays may be achieved by employing a matrix of  
9 pixels in the display which are energized by an X-Y sequential addressing scheme  
10 between two sets of perpendicular conductors. More advanced addressing schemes,  
11 applied predominantly to twisted nematic liquid crystal displays, use arrays of thin  
12 film transistors to control driving voltages at the individual pixels.

13  
14           Contrast and stability of relative gray scale intensities are important attributes  
15 in determining the quality of a liquid crystal display. The primary factor limiting the  
16 contrast achievable in a liquid crystal display is the amount of light which leaks  
17 through the display in the dark state. In addition, the contrast ratio of the liquid  
18 crystal device also depends on the viewing angle. The contrast ratio in a typical  
19 liquid crystal display is a maximum only within a narrow viewing angle centered near  
20 normal incidence and drops off as the angle of view is increased. This loss of  
21 contrast ratio is caused by light leaking through the black state pixel elements at large  
22 viewing angles. In color liquid crystal displays, such leakage also causes severe color  
23 shifts for both saturated and gray scale colors.

24  
25           The viewing zone of acceptable gray scale stability in a typical prior art  
26 twisted nematic liquid crystal display is severely limited because, in addition to color  
27 shifts caused by dark state leakage, the optical anisotropy of the liquid crystal  
28 molecules results in large variations in gray level transmission, i.e., a shift in the

3

1 brightness-voltage curve, as a function of viewing angle. The variation is often  
2 severe enough that, at extreme vertical angles, some of the gray levels reverse their  
3 transmission levels. These limitations are particularly important for applications  
4 requiring a very high quality display, such as in avionics, where viewing of cockpit  
5 displays from both pilot and copilot seating positions is important. Such high  
6 information content displays require that the relative gray level transmission be as  
7 invariant as possible with respect to viewing angle. It would be a significant  
8 improvement in the art to provide a liquid crystal display capable of presenting a high  
9 quality, high contrast image over a wide field of view.

10

11 Figures 1a and 1b show a conventional normally, white, twisted nematic liquid  
12 crystal display 100 including a polarizer 105 and an analyzer 110. The polarizer 105  
13 and the analyzer 110 are each bonded to glass substrates (not shown), such that the  
14 polarization axis of the analyzer 110 is perpendicular to that of the polarizer 105. The  
15 figures also show a light source 130 and a viewer 135.

16

17 An area between the polarizer 105 and the analyzer 110 contains a nematic  
18 liquid crystal material. The nematic phase is a fluid state of matter whose constituent  
19 molecules show long range correlation of their angular orientation (they are contained  
20 to have their long axes generally be parallel to one another), but no long range  
21 correlation of their positions in space as would be the case in a crystalline solid. The  
22 average orientation of the nematic molecules' long axes at any point in the material is  
23 called the director.

24

25 In the normally white configuration of Figures 1a and 1b, a "nonselect" area  
26 115 (no applied voltage) appears light, while a "select" area 120 (those which are  
27 energized by an applied voltage) appear dark. In the nonselect area 115 the liquid  
28 crystal molecules are constrained to adopt the helical structure shown in the figure

1 with their molecular long axes parallel to the glass substrates. In the select area 120  
2 the liquid crystal molecules tend to tilt and rotate toward alignment with the applied  
3 electric field. The alignment state with the liquid crystal molecules' long axes normal  
4 to the surfaces of the glass substrates is termed a homeotropic alignment. In practical  
5 twisted nematic displays the applied electric fields are not strong enough to yield  
6 completely homeotropic alignment.

7  
8 Many of the materials discussed in this document are birefringent. That is to  
9 say, they have varying indices of refraction depending on the direction of the electric  
10 vector of the light propagating through the material. The index of refraction is the  
11 ratio of the speed of light in a vacuum to that in the material. Materials such as  
12 liquid crystals that have different optical properties along different axes are said to be  
13 optically anisotropic. Materials without such angular variation are said to be  
14 isotropic. A uniaxial optical material has only one axis, the extraordinary axis, along  
15 which the electric vector of light interacts to yield a unique index of refraction ( $n_e$ ).  
16 This index will either be the highest or lowest found in the material. In a uniaxial  
17 material all possible axes perpendicular to the extraordinary axis will yield the same  
18 index of refraction (called the ordinary index,  $n_o$ ) for light whose electric vector lies  
19 in those directions; the material has ellipsoidal symmetry. If the extraordinary axis  
20 has the highest associated refractive index value of any axis the material is said to be  
21 positively birefringent. If it has the lowest refractive index, the material is said to be  
22 negatively birefringent. Light traversing a material such that its electric vector has  
23 components along both ordinary and extraordinary axes will have one polarized  
24 component retarded in its velocity as compared to the other. If a material has a  
25 unique axis which is associated with the highest refractive index, but the axes  
26 perpendicular to it have associated refractive indices which differ one to the other, the  
27 material is said to be optically biaxial and we will refer to the axis with the associated  
28 highest index as the principal optic axis. In this document the term "optical symmetry

1 axis" will be defined to mean the extraordinary axis in uniaxial materials and the  
2 principal optic axis in biaxial materials.

3  
4 Because the liquid crystals used for twisted nematic displays exhibit positive  
5 birefringence, the homeotropic alignment state would exhibit the optical symmetry of  
6 a positively birefringent C-plate. As is well known in the art, a C-plate is a uniaxial  
7 birefringent plate with its extraordinary axis (i.e., its optic or c-axis) perpendicular to  
8 the surface of the plate (parallel to the direction of normally incident light). In the  
9 select state, the liquid crystal in a normally white display would thus appear isotropic  
10 to normally incident light, which would be blocked by the crossed polarizers.

11  
12 One reason for the loss of contrast with increased viewing angle which occurs  
13 in a normally white display is that a homeotropic liquid crystal layer will not appear  
14 isotropic to off-normal light. Light propagating through the layer at off-normal angles  
15 appears in two modes due to the birefringence of the layer; a phase delay is intro-  
16 duced between those modes and increases with the incident angle of the light. This  
17 phase dependence on incidence angle introduces an ellipticity to the polarization state  
18 which is incompletely extinguished by the second polarizer, giving rise to light  
19 leakage. To correct for this effect, an optical compensating element must also have  
20 C-plate symmetry, but with negative birefringence ( $n_e < n_o$ ). Such a compensator  
21 will introduce a phase delay opposite in sign to the phase delay caused by the liquid  
22 crystal layer, thereby restoring the original polarization state and allowing light  
23 passing through energized areas of the layer to be blocked more completely by the  
24 output polarizer. C-plate compensation, however, does not impact the variation of  
25 gray scale with viewing angle, which is addressed by the present invention.

26  
27 Figure 2 depicts the coordinate system which is used to describe the  
28 orientation of both liquid crystal and birefringent compensator optic axes. Light

1 propagates toward the viewer **200** in the positive z direction **205** which, together with  
2 the x-axis **210** and the y-axis **215**, form a right-handed coordinate system.  
3 Backlighting is provided, as indicated by the arrows **220**, from the negative z  
4 direction. The polar tilt angle  $\Theta$  **225** is defined as the angle between the liquid crystal  
5 optic axis  $\hat{C}$  **230** and the x-y plane, measured from the x-y plane. The azimuthal or  
6 twist angle  $\Phi$  **235** is measured from the x-axis to the projection **240** of the optic axis  
7 onto the x-y plane.

## 9 2.2 Normally White Twisted Nematic LCDs

11 Figure 3 is a cross-sectional schematic view of a prior art twisted nematic,  
12 transmissive type normally white liquid crystal display. The display includes a  
13 polarizer layer **300** and an analyzer layer **305**, between which is positioned a liquid  
14 crystal layer **310**, consisting of a liquid crystal material in the nematic phase.

16 It is convenient in describing the orientation of various compensation elements  
17 of the display to refer to a normal axis perpendicular to the display, which is depicted  
18 by a dashed line **370**. In the case of a normally white display, the polarizer **300**  
19 (with a polarization direction in the plane of the drawing **315**) and the analyzer **305**  
20 (with a polarization direction into the plane of the drawing **320**) are oriented with  
21 their polarization directions at  $90^\circ$  to one another. (A polarizer **300** and an analyzer  
22 **305** both polarize electromagnetic fields. Typically, however, the term 'polarizer'  
23 refers to a polarizer element that is closest the source of light while the term  
24 'analyzer' refers to a polarizer element that is closest the viewer of the LCD.) The  
25 liquid crystal layer **310** is sandwiched between a pair of glass plates or substrates **340**  
26 and **345**. A first transparent electrode **325** and a second transparent electrode **330** are  
27 positioned on the glass substrates **340** and **345** adjacent to opposite surfaces of the  
28 liquid crystal layer **310** so that a voltage can be applied, by means of a voltage source

7

1 335, across the liquid crystal layer. As is explained below, the inner surfaces 346  
2 and 347 of the glass plates 340 and 345 and the transparent electrodes 325 and 330,  
3 which are proximate to the liquid crystal layer 310, can be physically or chemically  
4 treated to effect the desired liquid crystal orientation.

5  
6 As is well known in the LCD art (see, e.g., Kahn, The Molecular Physics of  
7 Liquid - Crystal Devices, Physics Today, Page 68, 1982), when the inner surfaces  
8 346 and 347 of the plates 340 and 345 are coated with a surface treatment for aligning  
9 the liquid crystal such as polyamide, buffed, and oriented with their buffed directions  
10 perpendicular, the director of the liquid crystal material, absent any applied electrical  
11 voltage, will tend to align with the buffed direction (known as the "rub direction") in  
12 the regions of the layer 310 proximate each of the plates 340 and 345. Furthermore,  
13 the director will twist smoothly with respect to the normal axis through an angle of  
14 90° along a path in the layer 310 from the first major surface adjacent to the plate  
15 340 (i.e., at the 310/340 interface) to the second major surface adjacent to the plate  
16 345 (i.e., at the 310/345 interface).

17  
18 In the absence of an applied electric field, the direction of polarization of  
19 incoming polarized light will be rotated by 90° in traveling through the liquid crystal  
20 layer 310. When the glass plates and the liquid crystal layer are placed between  
21 crossed polarizers, such as the polarizer 300 and the analyzer 305, light polarized by  
22 the polarizer and traversing the display, as exemplified by the light ray 350, will thus  
23 be aligned with the polarization direction of the analyzer 320 and therefore will pass  
24 through the analyzer 305.

25  
26 When a sufficient voltage is applied to the electrodes 325 and 330, however,  
27 the applied electric field causes the director of the liquid crystal material to tend to  
28 align parallel to the field. With the liquid crystal material in this state, light passed



1 by the polarizer 300, as illustrated by the light ray 355, will be extinguished by the  
2 analyzer 305. Thus, an energized pair of electrodes will produce a dark region in the  
3 display, while light passing through regions of the display which are not subject to an  
4 applied field will produce illuminated regions. As is well known in the LCD display  
5 art, an appropriate pattern of electrodes, activated in selected combinations, can be  
6 utilized in this manner to display alphanumeric or graphic information. As explained  
7 further below, one or more compensator layers, such as the layers 360 and 365, may  
8 be included in the display to improve the quality of the display.

### 10 2.3 Normally White Twisted Nematic LCD Characteristics

12 Figure 4 shows a calculated plot of liquid crystal director tilt as a function of  
13 position in a liquid crystal layer (where the cell gap has been normalized to unity) in  
14 a 90° twisted nematic cell. Typical distributions for molecular tilt angles when no  
15 voltage is applied (curve 400), under a typical select state voltage (curve 405), and  
16 under the application of several intermediate voltages chosen to yield linearly spaced  
17 gray levels (curves 410, 415, 420, 425, 430, and 435) are shown.

19 Figure 5 is a related plot for the same cell depicting the calculated twist angle  
20 (the azimuthal angle  $\Phi$  of the molecular long axes given an initial rub angle azimuth  
21 of 45°) of the liquid crystal molecules as a function of position in the cell. When  
22 there is no applied voltage, the twist is distributed evenly throughout the cell (straight  
23 line curve 500). Under a fully select state voltage, the twist angles are distributed as  
24 shown by the external, S-shaped curve 505. The twist distributions for gray levels  
25 are shown by the intermediate curves between the two curves 500 and 505.

27 As illustrated by Figures 4 and 5, when the fully selected voltage is applied,  
28 nearly all of the change in twist angle experienced by the liquid crystal molecules and



1 little of the change in tilt angle occurs in the central region of the cell. Because of  
2 this phenomena, the continuous variation of molecular orientation within the cell can  
3 be separated into three regions, each of which is characterized by its own optical  
4 symmetry. Thus, the central regions **440** (Figure 4) and **510** (Figure 5) can be  
5 considered as nominally homeotropic in the fully selected state, approximating the  
6 properties of a C-plate. The regions **445** and **450** (Figure 4) and **515** and **520** (Figure  
7 5), near each surface of the cell, behave as A-plates, each with its extraordinary axis  
8 aligned with the rub direction of the proximate substrate. Because there is essentially  
9 no twist in the molecules in the regions **445**, **450**, **515**, and **520**, the molecules are  
10 essentially aligned with the respective rub directions on either side of the liquid  
11 crystal layer. In addition, because the twist angle of the molecules in the regions **445**  
12 and **515** tends to be perpendicular to the twist angle of the molecules in the regions  
13 **450** and **520**, the effect of these two regions on light traveling through the cell tends  
14 to be canceled, leaving the middle C-plate region to exert the dominant influence.

15

### 16 2.3(a) C-Plate Compensation

17

18 As is well known in the art, a negative C-plate compensator is designed to  
19 correct for the angle dependent phase shift introduced by propagation through the  
20 central, approximately C-plate region of a LCD cell. Such a compensator is effective  
21 to the extent that the optical symmetry of the central region dominates the selected  
22 state of the liquid crystal cell, that is, the extent to which the molecules align with the  
23 applied field. This implies that negative C-plate compensation will work best when  
24 strong fields are used for the energized state as this makes the homeotropic  
25 approximation more nearly correct. The use of a C-plate has been demonstrated to  
26 significantly reduce the leakage of the dark state over an extended field of view, thus  
27 improving contrast and reducing color desaturation.

28

10

### 1 2.3(b) Gray Scale Stability

2

3 While the C-plate compensator may be used to improve contrast it does not  
4 improve grayscale stability. The problem of maintaining constant grayscale  
5 luminance differences over the field of view relates substantially to the brightness  
6 level changes for levels assigned between the select (black for a normally white  
7 display) and nonselect (white for a normally white display) states. This phenomenon  
8 is generally depicted using transmission, or brightness versus voltage (BV)  
9 electrooptic response curves for a display to which eight gray levels are assigned,  
10 from level 0 (the select black state) to level 7 (the nonselect white state). Gray levels  
11 between 0 and 7 are chosen by assigning them a set of voltages spaced linearly in  
12 brightness along the BV curve between the select and nonselect voltages.

13

14 Figure 6 is a plot of calculated BV curves for a normally white, 90° twisted  
15 nematic display as the horizontal viewing angle varies from 0° to 40° in 10°  
16 increments while the vertical viewing angle remains fixed at 0°. (The change in the  
17 BV curves with horizontal angle is first order independent of whether the horizontal  
18 deviation is to the left or right.) Note that the regions of each curve over which gray  
19 levels would be selected almost overlies one another for the various horizontal angles.  
20 This means that gray levels chosen to be linearly spaced at zero degrees would remain  
21 very nearly linear at even high horizontal viewing angles.

22

23 The gray scale linearity problem appears most predominantly when the vertical  
24 viewing angle varies. This is illustrated in Figure 7, which shows a series of BV  
25 curves for a normally white, 90° twisted nematic display as the vertical viewing angle  
26 varies from -10° to +30° while the horizontal viewing angle remains fixed at 0°. It  
27 can be observed that for angles below 0° (measured from the normal) the BV curves

1 shift to the right (higher voltage), and fall monotonically from their maximum but fail  
2 to reach zero.

3  
4 For angles above normal, the curves shift to the left and develop a rebound  
5 after an initial minimum. These effects can be explained by considering the  
6 perspectives of viewers looking at the display from above, at, and below normal, as  
7 shown in Figure 8. The critical feature to note is the relationship between the light  
8 traveling towards the viewer and the average liquid crystal director tilt at the center of  
9 a cell as voltage across the cell is increased.

10  
11 For instance, as the voltage across a cell is increased, the average liquid  
12 crystal director in the center of the cell tilts from a parallel (with respect to the  
13 polarizer **300** and analyzer **305**) orientation **815** toward a homeotropic one **825**. For  
14 the viewer at normal incidence **800**, retardation is highest at the nonselect state  
15 voltage and lowest at the select state voltage. When the anisotropy is zero, the  
16 polarization state of the light is unchanged and it is blocked by the analyzer. Thus,  
17 the viewer sees a monotonic decrease in brightness to zero with increasing voltage.

18  
19 Now consider the case of a positive vertical viewing direction (viewer above  
20 normal incidence **805**). At some intermediate voltage the average director **820** points  
21 toward the viewer and the retardation is minimal. Here the viewer sees a brightness  
22 with voltage that initially decreases toward a minimum, at the point of minimal retar-  
23 dation, and then increases.

24  
25 For the negative vertical viewing direction (viewer below normal incidence  
26 **810**), the average director always presents a large anisotropy to a light ray, even at  
27 the highest voltage. The viewer therefore sees a monotonic decrease in brightness.  
28 Furthermore, the average liquid crystal director is always oriented at a larger angle

12

1 with respect to the light ray for the below normal viewer **810** than it is for the normal  
2 incidence viewer **800**. Therefore, the anisotropy is greater and the brightness level is  
3 always higher in the negative vertical viewing direction than it is at normal incidence.  
4

5 This dependency, of an LCD's brightness versus viewing angle, has a  
6 profound impact on gray scale linearity. (Note that a voltage chosen to yield a 50%  
7 gray level on the 0° curve in Figure 7 yields a dark state on the +30° curve and  
8 approaches a fully white state at -10°.)  
9

### 10 2.3(c) O-Plate Gray Scale Compensation

11

12 To eliminate reversal of gray levels and improve gray scale stability, a  
13 birefringent O-plate compensator can be used. The O-plate compensator principle, as  
14 described in pending U.S. Patent Application Serial No. 223,251 filed on April 4,  
15 1994 utilizes a positive birefringent material with its principal optic axis oriented at a  
16 substantially oblique angle with respect to the plane of the display (hence the term  
17 "O-plate"). "Substantially oblique" implies an angle appreciably greater than 0° and  
18 less than 90°. O-plates have been utilized, for example, with angles relative to the  
19 plane of the display between 35° and 55°, typically at 45°. Moreover, O-plates with  
20 either uniaxial or biaxial materials can be used. O-plate compensators can be placed  
21 in a variety of locations between a LCD's polarizer layer and analyzer layer.  
22

23 In general, O-plate compensators may also include A-plates and/or negative C-  
24 plates as well as O-plates. As is well known in the art, an A-plate is a birefringent  
25 layer with its extraordinary axis (i.e., its c-axis) oriented parallel to the surface of the  
26 layer. Its a-axis is thus oriented normal to the surface (parallel to the direction of  
27 normally incident light), leading to its designation as an A-plate. A-plates may be

13

1 fabricated by the use of uniaxially stretched polymer films, such as polyvinyl alcohol,  
2 or other suitably oriented organic birefringent materials.

3  
4 A C-plate is a uniaxial birefringent layer with its extraordinary axis oriented  
5 perpendicular to the surface of the layer (parallel to the direction of normally incident  
6 light). Negatively birefringent C-plates may be fabricated by the use of uniaxially  
7 compressed polymers (See, e.g., Clerc, U.S. Patent No. 4,701,028), stretched poly-  
8 mer films, or by the use of physical vapor deposited inorganic thin films (See, e.g.,  
9 Yeh, U.S. Patent No. 5,196,953), for example.

10  
11 Oblique deposition of a thin film by physical vapor deposition is known to  
12 produce a film having birefringent properties (see, e.g. Motohiro, Applied Optics,  
13 Volume 28, Pages 2466 - 2482, 1989). By further exploiting the tilted orientation of  
14 the optical symmetry axis, this process can be used to fabricate O-plates. Such  
15 components are by their nature biaxial. Their growth characteristics generate a  
16 microscopic columnar structure. The angles of the columns are tipped towards the  
17 direction of the arriving vapor stream. A deposition angle (measured from normal) of  
18  $76^\circ$ , for example, results in a column angle of approximately  $45^\circ$ . The columns  
19 develop an elliptical cross-section as the result of shadowing. This elliptical cross-  
20 section gives rise to the biaxial character of the films. The birefringence, in  
21 magnitude and symmetry, is entirely attributable to the film microstructure and is  
22 referred to as form birefringence. These phenomena in thin films have been  
23 extensively studied and described by Macleod (Structure-related Optical Properties of  
24 Thin Films, J. Vac. Sci. Technol. A, Volume 4, No. 3, Pages 418-422, 1986).

25  
26 Uniaxial O-plate components can also be used to improve grayscale stability in  
27 normally white twisted nematic LCDs. These may be fabricated by the use of

14

1 suitably oriented organic birefringent materials. Those skilled in the art will  
2 recognize other means for fabricating both uniaxial and biaxial O-plates.

3  
4 Figures 9 and 10 show the effect that an O-plate compensator can have on  
5 normally white twisted nematic display. Figure 9 shows the BV curves for a  
6 normally white twisted nematic display using an O-plate compensator at a fixed  
7 vertical viewing angle of  $0^\circ$  and various horizontal viewing angles. Figure 10 shows  
8 the BV curves for a normally white twisted nematic display using an O-plate  
9 compensator at a fixed horizontal viewing angle of  $0^\circ$  and various vertical viewing  
10 angles. In this example, the O-plate layer is positioned adjacent to the liquid crystal  
11 layer on the source side of the display. A-plate layers are disposed on both sides of  
12 the O-plate/liquid crystal layer stack. The variation of the BV curves versus both  
13 horizontal and vertical viewing angles is greatly reduced relative to the  
14 uncompensated case shown in Figures 6 and 7.

15  
16 Elimination of gray scale reversal by the use of an O-plate compensator layer  
17 occurs in the following manner. In the positive vertical viewing direction, the  
18 retardation of the O-plate increases with viewing angle and tends to offset the  
19 decreasing retardation of the liquid crystal layer. When the viewer is looking down  
20 the axis of the average liquid crystal director, the presence of the O-plate prevents the  
21 layers between the two polarizers from appearing isotropic. Thus, the rebound in the  
22 BV curve, shown in Figure 7, is reduced and moved to higher voltages outside of the  
23 gray scale voltage range as shown in Figure 10.

24  
25 In the negative vertical viewing direction, the combination of an O-plate and  
26 an A-plate with their optic axes nominally at right angles tends to exhibit  
27 birefringence characteristics similar to that of a negative birefringence retarder with  
28 its optic axis oriented perpendicular to the plane containing the axes of the O-plate

15

1 and A-plate. The direction of this retarder axis is nominally parallel to the orientation  
2 of the average liquid crystal in the central region of the cell when it is driven at a  
3 voltage between select and nonselect states. Thus, the presence of an O-plate oriented  
4 in this manner tends to cancel the birefringence of the liquid crystal layer, pulling the  
5 BV curve down, or equivalently, moving it toward the direction of lower voltages  
6 (i.e., left) as shown in Figure 10. A similar effect occurs in the positive and negative  
7 horizontal viewing directions as shown in Figure 9 when compared to Figure 6.

8  
9 The overall effect of introducing an O-plate compensator in this manner is to  
10 eliminate large rebounds in the gray scale voltage region and reduce the left-to-right  
11 shift in the BV curves as the viewing angle is varied from negative to positive vertical  
12 angles.

13  
14 The orientations of the compensator optic axes can be carefully chosen so that  
15 the combined retardation effects cancel each other in the normal incidence viewing  
16 direction as well as minimize rebounds in the horizontal viewing direction.  
17 Combinations of more than one O-plate can be used as long as their orientations  
18 satisfy these requirements. Furthermore, negative C-plates can, for certain  
19 configurations, increase the contrast ratio at large fields of view, occasionally with  
20 some decrease in gray scale linearity.

#### 21 22 2.3(d) O-Plate Technology

23  
24 The liquid crystal layer, the compensator layer(s), the polarizer layer, and the  
25 analyzer layer can assume a variety of orientations relative to one another in a liquid  
26 crystal display. Some of the possible configurations which have been considered, and  
27 set out in pending U.S. Patent Application No. 223,251 are repeated in Table 1;  
28 where 'A' represents an A-plate, 'C' represents a C-plate, 'O' represents an O-

16

plate, 'LC' represents the liquid crystal, and 'OxO' represents crossed O-plates. Crossed O-plates are adjacent O-plates with their azimuthal angles  $\Phi$  235 nominally crossed, one oriented between  $0^\circ$  and  $90^\circ$ ; and the second oriented between  $90^\circ$  and  $180^\circ$ .

Table 1. Liquid Crystal Display Elements

| ← Toward Rear (Polarizer Side) |   |   |     | Toward Front (Analyzer Side) → |    |     |   |
|--------------------------------|---|---|-----|--------------------------------|----|-----|---|
|                                |   |   | O   | A                              | LC |     |   |
|                                |   |   | A   | O                              | LC |     |   |
|                                |   |   |     | O                              | LC | O   | A |
|                                |   | A | O   | A                              | LC |     |   |
|                                |   |   | O   | A                              | LC | A   |   |
|                                |   | O | A   | C                              | LC |     |   |
|                                |   |   | OxO | A                              | LC |     |   |
|                                |   | A | OxO | A                              | LC |     |   |
|                                |   |   |     | A                              | LC | OxO | A |
|                                | A | O | A   | C                              | LC |     |   |
|                                |   |   | A   | O                              | LC | O   | A |
|                                |   | A | O   | C                              | LC | C   | O |
|                                |   | A | O   | C                              | LC | C   | O |
|                                |   | C | A   | O                              | LC | O   | A |
|                                |   |   |     |                                |    |     | C |

The projections of the principal axes onto the plane of the display with respect to the liquid crystal director can vary with the embodiment. In some cases, for example with two O-plates, the O-plate axis projections are at  $45^\circ$  with respect to the average liquid crystal director, while in others, the O-plate axis is parallel with the liquid crystal director.

Crossed O-plate (OxO) designs that are further compensated with A-plates provide additional design flexibility. The choice of A-plate value is not critical as



1 such designs can be adjusted by varying the relative orientations of the A-plates.  
2 Thus, it is possible to generate desired solutions with commercially available A-plate  
3 retardation values.  
4

#### 5 2.4 Twisted and Splayed O-plates

6

7 Computer modeling and display cell measurements show the optical behavior  
8 of the biaxial O-plate based compensators produced from  $Ta_2O_5$  to be qualitatively  
9 different from that of compensators produced from uniaxial polymerized liquid crystal  
10 materials. For some applications, grayscale stability and contrast over field of view  
11 properties produced by the biaxial components are preferred. However, organic  
12 compensator films based on uniaxial liquid crystal polymers are very attractive  
13 because they both make a wider range of material parameters accessible and also  
14 allow the possibility of inexpensive mass production of compensator components.  
15 Therefore a goal of further compensator development has been to produce a thin film  
16 organic O-plate layer which shows biaxial character.  
17

18 It is believed that biaxial compensator components produce qualitatively  
19 different optical performance because the deformation structure of the partially  
20 selected liquid crystal layer in a twisted nematic display has some biaxial character  
21 itself. In the nonselect state the liquid crystal has a helical structure which rotates the  
22 polarization state of incident light by means of the process of adiabatic waveguiding  
23 as described above. As the electric field across the liquid crystal layer is increased  
24 the helical structure is distorted and the efficiency of the waveguide decreases. Some  
25 portion of the light is no longer efficiently rotated and begins as a result to lag the  
26 rotation of the liquid crystal helical structure. This light encounters a medium  
27 intermediate in refractive index between the ordinary and extraordinary index values.  
28 The net result is that the medium appears biaxial.

1           The O-plate solution to the compensation of the twisted nematic display was  
2 based on the approximate model described above that the liquid crystal layer in the  
3 select state of the twisted nematic display could be divided into three regions, two A-  
4 plate-like regions and a central region of pseudo-homeotropic character. O-plate  
5 compensated displays, however, operate with the full-on black state accessible at  
6 voltages considerably reduced from the black state voltage in uncompensated displays.  
7 At these reduced drive voltages, the liquid crystal layer central region is unlikely to  
8 have completely deformed to the pseudo-homeotropic state, and the three region  
9 model becomes even more approximate. At these intermediate voltages the liquid  
10 crystal layer central region will still be significantly splayed and twisted yielding the  
11 biaxial character described in the above paragraph.

12  
13           The intuitive approach to compensator development has been that like  
14 compensates like, i.e., compensators should have similar or complementary optical  
15 symmetries to the liquid crystal layers they are intended to compensate. Based on this  
16 idea and the analysis in the above paragraphs it was decided to investigate splayed and  
17 twisted O-plate structures with the idea that they could be substituted into the existing  
18 O-plate configurations described above with resulting improved performance.

## 19 20   2.5   Summary

21  
22           When viewed at an angles nearly normal to their surfaces twisted nematic  
23 liquid crystal displays provide high quality optical characteristics, but at large viewing  
24 angles the image tends to degrade and exhibit poor contrast and grayscale stability.  
25 Compensator configurations containing O-plates have been shown to produce greatly  
26 improved contrast and grayscale stability over field of view. O-plate configurations  
27 with biaxial optical symmetry have given qualitatively different performance than  
28 those with uniaxial symmetry. It is believed that this is true because biaxial O-plates

19

1 more closely approximate the symmetry of an energized twisted nematic liquid crystal  
2 layer. Currently available biaxial O-plates are produced using an expensive vacuum  
3 deposition process, and a more cost effective large volume process is desired.

4  
5 It is the goal of this invention to provide a process for producing O-plates  
6 which have the desired biaxial symmetry using an inexpensive fabrication process  
7 which is capable of being scaled up to large volume production.

### 8 9 **3. SUMMARY OF THE INVENTION**

10  
11 The compensator design of this invention, which includes a positively  
12 birefringent twisted and/or splayed O-plate layer, makes possible a significant  
13 improvement in the gray scale properties and contrast ratios of liquid crystal displays  
14 (LCDs) over a wide range of viewing angles. By making use of polymerized thin  
15 films of organic liquid crystal materials the compensators are able to duplicate the  
16 performance of existing biaxial inorganic O-plate compensators, but at reduced cost  
17 and with more design flexibility.

18  
19 An O-plate compensator comprising an organic liquid crystal polymer thin  
20 film, and methods for fabricating the same, are disclosed. On the microscopic scale  
21 the film is composed of a polymerized birefringent liquid crystal material which is  
22 uniaxial or near uniaxial in character. The liquid crystal material is constrained such  
23 that its optical symmetry axis is, on average, oriented obliquely with the surface of  
24 the film. Within this constraint, the direction of the material's optical symmetry axis  
25 is allowed to vary continuously along the axis normal to the film surface. If the  
26 variation is in the tilt angle of the optical symmetry axis relative to the film surface  
27 the liquid crystal material will have splayed structure. If the variation is in the

20

1 azimuthal angle of the optical symmetry axis the material will have twisted structure.  
2 The invention can comprise either angular variation or both in combination.

3 The oblique orientation of the liquid crystal director, which is parallel to the  
4 optical symmetry axis, is achieved by casting an organic thin film onto a surface  
5 specially prepared for orienting liquid crystal monomers, such as oblique SiO,  
6 mechanically rubbed polymers, etc. The variation in tilt angle through the layer is  
7 achieved by selecting a liquid crystalline material such that its tilt angle at the  
8 substrate surface is substantially different from that at the liquid crystal air interface.  
9 The variation in azimuthal angle through the layer is achieved by doping the liquid  
10 crystal monomer with a chiral additive in sufficient quantity so as to provide the  
11 proper helical pitch along the axis normal to the film surface. The film can either be  
12 cast from a solution of the liquid crystal polymer or from a reactive liquid crystal  
13 monomer. Any solvent that may be used during the fabrication process is evaporated  
14 off and the organic thin film is annealed at a temperature in its nematic phase. If a  
15 reactive monomer is used, the film is then photopolymerized. Finally, the film is  
16 thermally quenched to 'freeze' in the liquid crystalline structure. Alternative  
17 embodiments of the splayed / twisted O-plate include the use of nematic or smectic C  
18 materials. Fabrication techniques employing these materials are described.

#### 19 20 4. BRIEF DESCRIPTION OF DRAWINGS

21  
22 Figures 1a and 1b show, in overview, the operation of a normally white, 90°  
23 twisted nematic liquid crystal display.

24  
25 Figure 2 depicts a coordinate system that is used to specify component  
26 orientations in the description of this invention.

21

1           Figure 3 is a cross-sectional schematic view of a 90° twisted nematic,  
2 transmissive type normally white liquid crystal display.

3           Figure 4 is a plot of the tilt angle of the director (in degrees along the vertical  
4 axis) as a function of position (as a fraction of the depth along the horizontal axis) in  
5 a 90° twisted nematic liquid crystal cell.

6  
7           Figure 5 is a related plot for the cell shown in Figure 4, depicting the twist  
8 angle of the liquid crystal molecules as a function of their position in the cell.

9  
10          Figure 6 is a plot of calculated brightness vs. voltage electrooptic curves at a  
11 variety of horizontal viewing directions for a typical twisted nematic display without  
12 the benefit of O-plate gray scale compensation.

13  
14          Figure 7 is a plot of calculated brightness vs. voltage electrooptic curves at a  
15 variety of vertical viewing directions for a typical twisted nematic display without the  
16 benefit of O-plate gray scale compensation.

17  
18          Figure 8 is an illustration of the viewer's perspective relative to the average  
19 director orientation of a liquid crystal display.

20  
21          Figure 9 is a plot of calculated brightness versus voltage electrooptic curves at  
22 a variety of horizontal viewing directions for a typical twisted nematic display with  
23 the benefit of O-plate gray scale compensation.

24  
25          Figure 10 is a plot of calculated brightness versus voltage electrooptic curves  
26 at a variety of vertical viewing directions for a typical twisted nematic display with  
27 the benefit of O-plate gray scale compensation.

22

1           Figure 11 is a cross-sectional view of a normally white, twisted nematic liquid  
2 crystal display in accordance with the invention.

3  
4           Figure 12 is a cross-sectional schematic view of one embodiment of a  
5 twisted/splayed O-plate compensator stack produced by polymerization of nematic  
6 liquid crystal monomers.

7  
8           Figure 13 is a cross-sectional schematic view of one embodiment of a twisted  
9 O-plate compensator stack produced by polymerization of smectic C liquid crystal  
10 monomers.

11  
12           Figure 14 is a cross-sectional schematic view of one embodiment of a  
13 multilayer twisted/splayed O-plate compensator stack produced by polymerization of  
14 nematic liquid crystal monomers.

## 15 16   **5. DETAILED DESCRIPTION OF A SPECIFIC EMBODIMENTS**

17  
18           Illustrative embodiments of the invention are described below as they might be  
19 implemented using polymeric liquid crystalline thin films to create a twisted and/or  
20 splayed O-plate compensator. In the interest of clarity, not all features of an actual  
21 implementation are described in this specification. It will of course be appreciated  
22 that in the development of any such actual implementation (as in any development  
23 project), numerous implementation-specific decisions must be made to achieve the de-  
24 velopers' specific goals and subgoals, such as compliance with system- and business-  
25 related constraints, which will vary from one implementation to another. Moreover,  
26 it will be appreciated that such a development effort might be complex and time-  
27 consuming, but would nevertheless be a routine undertaking of device engineering for  
28 those of ordinary skill having the benefit of this disclosure.

1    5.1 Introduction

2  
3           Figure 11 shows an illustrative embodiment of a liquid crystal display (LCD)  
4 system in accordance with the invention, that uses a single twisted and/or splayed O-  
5 plate compensator **1100** disposed between a polarizer **1105** and a liquid crystal layer  
6 **1110**. The O-plate layer **1100** comprises birefringent liquid crystal polymer layer  
7 having an optical symmetry axis **1120** oriented, on average, at a tilt angle **1125**,  
8 relative to the surface of the liquid crystal polymer layer **1110**, of approximately 20°  
9 to 80°. Alternatively, the O-plate layer could be located between liquid crystal layer  
10 **1110** and an analyzer **1115**, or in both locations. More details on the structure of the  
11 twisted and/or splayed O-plate layer are given below.

12  
13           The decision as to where to place the O-plate compensator is purely a design  
14 choice and is, generally, based on the optical requirements of the display being  
15 compensated and on the manufacturing and cost constraints of the display system.

16  
17           In general, O-plate compensators may also include A-plates and/or negative C-  
18 plates as well as O-plates. Twisted/splayed O-plate compensators may contain both  
19 twisted/splayed O-plates and simple O-plates. As is well known in the art, an A-plate  
20 is a birefringent layer with its extraordinary axis (i.e., its c-axis) oriented parallel to  
21 the surface of the layer. Its a-axis is thus oriented normal to the surface (parallel to  
22 the direction of normally incident light), leading to its designation as an A-plate. A-  
23 plates may be fabricated by the use of uniaxially stretched polymer films, such as  
24 polyvinyl alcohol, or other suitably oriented organic birefringent materials.

25

26



## 1 5.2 Nematic Embodiment

2  
3 Another illustrative embodiment, shown in Figure 12, includes a rigid glass  
4 substrate 1200, an alignment layer 1205, a polymerized pretilt nematic liquid crystal  
5 layer 1207, an alignment/pretilt layer interface 1205/1207, a polymerized nematic  
6 liquid crystal monomer layer 1210, a pretilt/liquid crystal layer interface 1207/1210  
7 and a nematic/air interface 1212. The nematic material in the layer 1210 has been  
8 doped with a chiral dopant to yield a cholesteric pitch approximately 12 times the  
9 layer thickness, yielding a twist angle of approximately 30 degrees in the layer 1210.  
10 The liquid crystal layers are deposited in the form of polymerizable nematic monomer  
11 compounds doped with approximately 0.5% of Igracure-651, a photoinitiator.  
12

13 The alignment layer 1205 is produced by coating a surface of the substrate  
14 1200 with a polyamide material that produces a liquid crystal pretilt angle of from 1°  
15 to 10° in the layer 1207 at the alignment/pretilt layer interface 1205/1207. The  
16 alignment material is then rubbed so as to produce uniformly tilted alignment in the  
17 desired azimuthal orientation in the layer 1207.  
18

19 A thin film of liquid crystal monomer is applied to the alignment layer 1205  
20 using the technique of spin coating from a solution in an inert solvent. Other methods  
21 of coating the nematic material such as, for example, dip or slot-die coating can be  
22 used as well. The solution coated onto the surface of the alignment layer 1205 may  
23 contain prepolymerized liquid crystal side-chain polymers added as a viscosity  
24 modifier to improve coating wetting characteristics. In addition, the solution should  
25 contain a photoinitiator as stated above.  
26

27 After the nematic film has been applied to the alignment layer 1205, the  
28 solvent is driven off at elevated temperature producing the pretilt layer 1207. The

25



1 temperature of the pretilt layer 1207 is adjusted so as to produce the desired nematic  
2 phase in the layer 1207 and the desired tilt angle at the 1207/1210 interface. The  
3 liquid crystal film is then illuminated with ultraviolet light (actinic radiation) at a  
4 wavelength of approximately 360 nanometers with a total exposure sufficient to  
5 polymerize the monomer to liquid crystal polymer film, thereby preserving the order  
6 of the liquid crystal phase of the layer 1207 and the desired tilt angle at the  
7 1207/1210 interface.

8 The purpose of the liquid crystal pretilt layer 1207 is to provide a high pretilt  
9 alignment layer for the liquid crystal monomer used to produce the actual  
10 compensator layer 1210. If the pretilt layer 1207 is thick enough, the pretilt angle of  
11 the material at the surface of the layer 1210 will be dictated by the nematic/air tilt  
12 angle of the material at the surface of the layer 1207. After the application of the  
13 liquid crystal layer 1210, the nematic/air interface of the layer 1207 becomes the  
14 pretilt/liquid crystal interface 1207/1210. The nematic material in the layer 1207  
15 undergoes an incremental tilting, referred to as a continuous splay/bend deformation,  
16 from the low tilt angle at the 1205/1207 interface up to the desired tilt angle at the  
17 1207/1210 interface. For the layer 1207, the difference between the tilt angle at the  
18 1205/1207 interface and the tilt angle at the 1207/1210 interface is referred to as the  
19 splay angle. The pretilt layer 1207 should be sufficiently thin, approximately 100  
20 nm., when compared to the thickness of layer the 1210, approximately 1  $\mu\text{m.}$ , such  
21 that its optical retardation will be insignificant as compared to the overall retardation  
22 of the compensator stack.

23  
24 Other possible alignment layer materials could be substituted for the layers  
25 1205 and 1207 to give the required  $30^\circ$  pretilt angle and azimuthal alignment for the  
26 liquid crystal layer 1210. Such materials could include, for example, mixtures of  
27 homogenous and homeotropic alignment materials that are then rubbed.

26

1           After the layer **1207** has been prepared, another layer of nematic monomer  
2 solution is deposited on its surface in a manner entirely analogous to the original  
3 deposition of the layer **1207**. After the solvent has been driven off and the material  
4 polymerized with UV irradiation, this material constitutes layer **1210**. Other methods  
5 for polymerizing thin monomer films well known in the art could be used.

6  
7           The material used to prepare the layer **1210** is similar to that in **1207** with a  
8 few exceptions. The material in the layer **1210** has been doped with a chiral material  
9 as described above so as to produce an approximately 30° twist of the azimuthal  
10 orientation of the nematic optical symmetry axis (extraordinary axis). This variation  
11 in azimuthal orientation occurs about an axis normal to the layer **1210** from top to  
12 bottom through the layer **1210**. The twisted and splayed structure of the layer **1210** is  
13 represented by the liquid crystal side chains or moieties **1220**. The variation in the  
14 orientation of the optical symmetry axis of the layer **1210** is represented by the arrows  
15 **1225** projected from the moieties **1220**. As can be seen from Figure 12, the optical  
16 symmetry axis varies through the layer **1210** according to the tilted and azimuthal  
17 orientation of the moieties **1220** of the layer **1210**.

18  
19           In this particular embodiment, the material used to produce the layer **1210** has  
20 been chosen to have a tilt angle of 60° at the nematic/air interface **1212** (the 30°  
21 pretilt angle at the **1207/1210** interface plus a 30° splay angle through the layer  
22 **1210**). The solution concentration of the nematic monomer, concentration of  
23 prepolymerized nematic polymer, and the deposition parameters are selected such that  
24 the layer **1210** is of the proper thickness to provide the required retardation value, on  
25 the order of 1  $\mu\text{m}$ . A splayed/twisted O-plate layer prepared in this way will have a  
26 varying optical symmetry axis with a splay angle of 30°, a twist angle of 30°, and an  
27 average tilt angle of 45°.

27

### 1 5.3 Smectic C Embodiment

2

3 An alternative embodiment is shown in Figure 13. As before, the  
4 compensator system comprises a rigid glass substrate **1300**, an alignment layer **1305**,  
5 a polymerized liquid crystal layer **1310**, a liquid crystal/alignment layer interface  
6 **1305/1310**, and a liquid crystal/air interface **1315**. In this embodiment, however, the  
7 polymerized liquid crystal layer **1310** has a smectic C phase and a smectic C  
8 intralayer tilt angle of  $45^\circ$ . As such, the desired intralayer tilt angle ( $45^\circ$ ) of the  
9 liquid crystal layer **1310** remains constant through the layer **1310**.

10

11 A liquid crystal material with a smectic C to nematic phase transition rather  
12 than a smectic C to smectic A phase transition is preferred because such materials  
13 tend to have large, in the range of  $10^\circ$  to  $45^\circ$ , smectic C intralayer tilt angles.

14

15 As in the nematic embodiment, an alignment layer **1305** is produced on the  
16 surface of the substrate **1300**. In one embodiment, the alignment layer **1305** material  
17 is a thin film of silicon monoxide,  $\text{SiO}_x$ , obliquely deposited at a polar angle of  
18 approximately  $60^\circ$  and overcoated with a thin film of egg lecithin, a homeotropic  
19 alignment material. This alignment layer **1305** produces a liquid crystal pretilt angle  
20 for nematic materials of approximately  $80^\circ$  and a uniform azimuthal direction of the  
21 liquid crystal director which is determined by the azimuthal  $\text{SiO}_x$  deposition angle.

22

23 Next, a thin film of polymerizable liquid crystal monomer is laid down on the  
24 alignment layer **1305** using techniques detailed in the nematic embodiment. The  
25 liquid crystal monomer is doped with a chiral material such that in its smectic C  
26 phase it will have a chiral pitch approximately 12 times the thickness of the layer  
27 **1310**, yielding a twist angle of approximately 30 degrees through the layer **1310**.  
28 After the solvent has been removed, the temperature of the monomer film is raised

1 high enough to transform it into the nematic phase. The nematic phase then adopts a  
2 uniform pre-tilt angle of  $80^\circ$  at the liquid crystal/alignment layer interface **1305/1310**.  
3 The temperature is then slowly decreased, eg., at a rate of approximately  $0.1^\circ\text{C}$  per  
4 second, transforming the liquid crystal film into its smectic C phase.

5  
6 This process forms smectic C layers parallel to the surface of the alignment  
7 layer **1305** with the molecules initially adopting a smectic C intralayer tilt angle of  
8 approximately  $0^\circ$ . As the temperature of the film is lowered further through its  
9 smectic C temperature range, the smectic C intralayer tilt angle increases. (The  
10 azimuthal direction of the molecules is determined by the azimuthal  $\text{SiO}_x$  deposition  
11 angle.) At a temperature just above the material's melting point, the smectic  
12 intralayer tilt angle reaches a maximum value of approximately  $45^\circ$ . Furthermore, in  
13 a smectic C material, the polar tilt angle at the liquid crystal/air interface **1312** does  
14 not influence the tilt angle of the bulk liquid crystal material in the layer **1310**.  
15 Various other ways to form smectic layers parallel to the alignment layer will be  
16 recognized by those skilled in the art.

17  
18 As stated above, the liquid crystal monomer is doped with a chiral material to  
19 produce an approximately  $30^\circ$  twist of the azimuthal orientation of the liquid crystal  
20 optical symmetry axis (extraordinary axis). This variation in azimuthal orientation  
21 occurs about an axis normal to the layer **1310** from top to bottom through the layer  
22 **1310**. The azimuthal orientation of moieties **1320** at the liquid crystal/air interface  
23 **1312** is determined by a combination of the azimuthal orientation of the liquid crystal  
24 at the liquid crystal/alignment layer interface **1305/1310**, the pitch of the chiral helix  
25 in the smectic C material, and the smectic C film layer thickness. The tilted helical  
26 structure of the smectic material in the layer **1310** is represented by the moieties  
27 **1320**. The variation in the orientation of the optical symmetry axis of the layer **1310**  
28 is represented by the arrows **1325** projected from the moieties **1320**. As can be seen

1 from Figure 13, the optical symmetry axis varies through the layer **1310** according to  
2 the tilted and azimuthal orientation of the moieties **1320** of the layer **1310**.

3  
4 Upon obtaining the desired intralayer tilt angle in the liquid crystal film and  
5 the desired azimuthal orientation, the liquid crystal monomer film is irradiated with  
6 ultraviolet light that is sufficient to polymerize the monomer to a polymeric film **1310**  
7 in which the order of the smectic liquid crystal is preserved., typically  $4 - 10 \text{ J/cm}^2$ .  
8 Other polymerization techniques for thin films are well known in the art and may also  
9 be used. The result of this process is a thin film or liquid crystal layer **1310** of liquid  
10 crystal polymer that is positively birefringent and has an optical symmetry axis that is  
11 oriented at a polar tilt angle of approximately  $45^\circ$  with a twist angle of approximately  
12  $30^\circ$ .

#### 13 14 5.4 Multilayer Embodiment

15  
16 A further illustrative liquid crystal display system, see Figure 14, includes a  
17 rigid glass substrate **1400**, an alignment layer **1405**, polymerized nematic liquid  
18 crystal pretilt layer **1410**, polymerized nematic liquid crystal layers **1415**, **1420**, **1425**,  
19 and **1430**; a liquid crystal/alignment layer interface **1405/1410**, liquid crystal/liquid  
20 crystal interfaces **1410/1415**, **1415/1420**, **1420/1425**, and **1425/1430**; and a liquid  
21 crystal/air interface **1435**.

22  
23 The alignment layer **1405**, the pretilt layer **1410** and the liquid crystal layer  
24 **1415** are produced by methods identical to layers **1205**, **1210**, and **1215** in the  
25 nematic embodiment above with the following exceptions. The liquid crystal in the  
26 pretilt layer **1410** is chosen to produce a tilt angle of approximately  $40^\circ$  at the  
27 **1410/1415** interface after the liquid crystal layer **1415** is applied. As in the nematic  
28 embodiment above, the function of the layer **1410** is to increase the pretilt of the layer

1    **1415** to  $40^\circ$  without altering the azimuthal orientation of the moieties **1416** in the  
2    layer **1415**. The liquid crystal in the layer **1415** is chosen to produce a tilt angle of  
3     $50^\circ$  at the **1415/1420** interface after it is polymerized, thereby yielding a splay angle  
4    of approximately  $10^\circ$  through the layer **1415**.

5  
6        The liquid crystal in the layer **1415** is also doped with a chiral additive so as  
7    to have a left handed cholesteric pitch of 24 times the layer thickness of the layer  
8    **1415**, yielding an approximately  $15^\circ$  twist of the azimuthal orientation of the nematic  
9    optical symmetry axis (extraordinary axis) through the layer **1415**. This variation in  
10   azimuthal orientation occurs about an axis normal to the layer **1415** from top to  
11   bottom through the layer **1415**. The twisted and splayed structure of the layer **1415** is  
12   represented by the liquid crystal side chains or moieties **1416**. The variation in the  
13   orientation of the optical symmetry axis of the layer **1415** is represented by the arrows  
14   **1417** projected from the moieties **1416**. As can be seen from Figure 14, the optical  
15   symmetry axis of the layers **1415**, **1420**, **1425** and **1430** (represented by arrows **1417**,  
16   **1423**, **1427** and **1433**) vary through the respective layers **1415**, **1420**, **1425** and **1430**  
17   according to the tilted and azimuthal orientation of the respective moieties **1416**,  
18   **1422**, **1426** and **1432** of the respective layers **1415**, **1420**, **1425** and **1430**.

19  
20        After the layer **1415** has been polymerized by irradiation with UV light, the  
21   layer **1420** is applied over it. The layer **1415** functions to align layer **1420** to the  
22   proper azimuthal and pretilt ( $50^\circ$ ) orientations at the **1415/1420** interface in a manner  
23   analogous to the pretilt layer **1410** at the interface **1410/1415**. The liquid crystal in  
24   the layer **1420** is doped with a chiral additive so as to have a right handed cholesteric  
25   pitch of 24 times the thickness of the layer **1420**. As such, the layer **1420** will have a  
26   twist structure equal in magnitude ( $15^\circ$ ) yet opposite in sense to that in the layer  
27   **1415**. Additionally, the layer **1420** will have a splay angle ( $10^\circ$ ) equal in magnitude

1 to the splay angle of the layer 1415 but opposite in sign, thereby producing a 40° tilt  
2 angle in the layer 1420 at the interface 1420/1425.

3  
4 In this particular embodiment, the layer 1415 is identical to the layer 1425,  
5 and layer 1420 is identical to layer 1430. The present invention, however,  
6 encompasses a multilayer embodiment in which the magnitude and sign of the tilt,  
7 splay and/or twist orientations of the successive and/or alternating layers are different  
8 in magnitude and/or in sign. Each successive layer is deposited over the preceding  
9 layer after the preceding layer has been cured with UV radiation. Each succeeding  
10 layer can be azimuthally aligned and pretitled at the interface by the preceding layer.  
11 Other methods of polymerizing the succeeding layers may also be used. These could  
12 include thermal cure and other irradiation techniques.

13  
14 The purpose of producing a layered alternating splay/twist O-plate structure as  
15 is described in this embodiment is to yield a compensator which has a biaxial nature,  
16 but which has minimum twisting power for polarized light which transits the  
17 compensator stack.

## 18 19 5.5 Possible Variations

20  
21 For each of the previous illustrative embodiments, a number of variations are  
22 possible and would be obvious to one skilled in the art of liquid crystal display  
23 devices. For example, other possible substrate materials could include non-  
24 birefringent polymer films. The polymerizable liquid crystal monomer material may  
25 include, as a constituent, molecules that contain two reactive functional groups and  
26 therefore can act as cross-linking agents. Other polar tilt angles at the liquid  
27 crystal/alignment layer interface can be achieved by suitable selection of reactive  
28 liquid crystals, modification of the alignment materials, rubbing conditions, etc.

32

1 Furthermore, a non-reactive liquid crystal material can be combined with the  
2 polymerizable liquid crystal. The resulting liquid crystal polymer film would then  
3 have the properties of a plastic or gel. The liquid crystal material could also contain  
4 a polymer, liquid crystal polymer, or oligomer that increases the viscosity of the  
5 liquid crystal mixture and improves the film forming properties thereof.

6  
7 Additionally, the various embodiments have been described above with specific  
8 pretilt, splay and twist orientations and/or angles, but the present invention is not  
9 limited to specific angles or orientations. Finally, the multilayer embodiment has  
10 been specifically described with nematic layers but the multilayer embodiment can be  
11 of multiple smectic C layers.

## 12 13 6. BIBLIOGRAPHY

- 14  
15 a. Clerc et al., U.S. Patent No. 4,701,028.  
16 b. Kahn, The Molecular Physics of Liquid-Crystal Devices, Physics Today, Page  
17 66, May 1982.  
18 c. Macleod, Structure-related Optical Properties of Thin Films, J. Vac. Sci.  
19 Technol. A, Volume 4, No. 3, Pages 418-422, 1986.  
20 d. Motohiro and Taga, Thin Film Retardation Plate by Oblique Deposition, Appl.  
21 Opt., vol. 28, No. 13, Pages 2466-2482, 1989.  
22 e. Yeh et al., "Compensator for Liquid Crystal Display Having Two Types Of  
23 Layers With Different Refractive Indices Alternating", U.S. Patent No.  
24 5,196,953.

25  
26  
27 It will be appreciated by those of ordinary skill having the benefit of this dis-  
28 closure that numerous variations from the foregoing illustration will be possible with-



1 out departing from the inventive concept described herein. Accordingly, it is the  
2 claims set forth below, and not merely the foregoing illustrative embodiments, which  
3 are intended to define the exclusive rights claimed in this application program.

34